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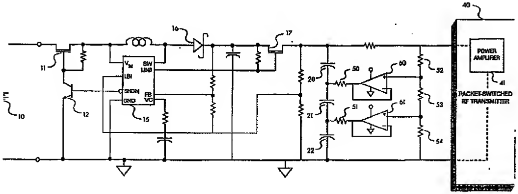
(54) Improved power supply system for a packet-switched radio transmitter

(57) An improved power supply system involves load-leveling the large transient currents drawn by a high power, low duty-cycle load application circuit by means of a high performance capacitive charge storage device, such as a super-capacitor or a network of super-capacitors. The improved power supply system allows the high power load application circuit to be driven by a limited energy power source, such as a battery or the power supplied to a PCMCIA slot by a host computer. When the input voltage source is a battery, the improved power supply system allows for a substantial increase in the battery's operational life. The inventive system is particularly useful for managing power supply requirements for miniaturized wireless transmission systems, such as two-way pagers or radio modems, which employ low duty-cycle packet-switched RF transmitters.

Figure 5



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Description

BACKGROUND OF THE INVENTION

[0001] The present invention is directed toward the field of electrical power supply management circuitry, and in particular, to improved power supplies for low duty-cycle radio frequency ("RF") communication systems, such as digital, packet-switched RF transmission devices. These types of systems typically include miniaturized low voltage power sources, and are characterized by relatively long time intervals between RF transmissions. These systems, however, require that large bursts of power be delivered quickly for transmitter operation. The present invention allows for substantial improvements in efficiency and effective battery life for such systems. In a conventional prior art digital RF communication system, the transmitter circuitry modulates a carrier signal with a binary signal, producing a transmitted RF sequence representing binary ones and zeroes. Under a packet-switched communications protocol, these binary one and zero bits are transmitted in discrete blocks ("packets") consisting of address, data, sender identification, and other control bits. The packets are not transmitted continuously, but are stored until a packet or group of packets is ready for transmission. Thus, the power amplifier for a conventional packet-switched transmitter requires high input power only for short intervals, with relatively long low power quiescent periods in-between. As a result, the "duty-cycle" of such a system, i.e., the percentage of the total cycle time taken by the active transmission time is quite low.

[0002] Despite the low duty-cycle of the system, the power amplifier for a conventional packet-switched transmitter produces a very high current load, drawing about 1000 milliamps (mA) or more for one second during transmission. In prior art technologies, the RF transmitter was often powered directly from a conventional battery; however, the high power demands of the power amplifier imposed severe limitations on the type of battery technology that could be used. Conventional carbon-based batteries typically could not provide sufficient instantaneous power for such a transmitter. While a conventional alkaline cell could have powered the transmitter, the equivalent resistance of such a cell will climb rapidly as the cell is depleted. This increasing resistance reduces the current that can be supplied to the transmitter and reduces the usable battery life. Ultimately, the instantaneous current supplied by an alkaline cell will fall below the power amplifier's input power requirements. In the prior art, this level of depletion would typically be reached while the battery still had significant capacity remaining; thus, a user would be required to replace a reasonably fresh battery.

[0003] Alternatively, some prior art packet-switched systems, such as portable RF modems, used internal, single-use alkaline cells to charge a rechargeable battery stack. This battery stack in turn supplied the power for the RF transmitter. These systems were quite inefficient, however, because the battery stack would be overcharged, storing up far more power than that normally needed for sending a short packet-switched message. Also, such power supply circuitry consumed space, was expensive, and was unnecessarily complex. In addition, conventional rechargeable batteries, such as a Ni-Cd cell stack, have a long charge cycle, sometimes measured in hours, and could withstand only a limited number of charge cycles, perhaps about 300, before such batteries themselves would have to be replaced.

[0004] Other types of batteries exist that provide high energy storage, but are incompatible with conventional packet-switched RF transmission systems because of the high equivalent series resistance ("ESR") of the cell. For example, a single-use lithium cell, such as an Ultralife® 9-volt cell (a registered trademark of Ultralife Batteries, Inc. of New York, NY), has a very high stored energy rating of 9,000 milliwatt hours (mWhrs), as compared with only about 800 mWhrs for the typical rechargeable stack, or about 3000 mWhrs for a typical 9-volt alkaline cell. Unfortunately, a lithium cell has an ESR of over 10 ohms, even when new, and can only deliver a peak instantaneous power of about 0.75 watts. Because the typical RF transmitter requires 5 watts of input power and cannot tolerate an ESR of greater than 2 ohms, a cell such as the Ultralife® is not a viable power source despite its large storage capacity.

[0005] Similarly, a host computer auxiliary device power pin would be unsuitable to power a conventional packet-switched RF transmitter. Because most host computers can supply only about 0.75 watts to a PCMCIA slot or other types of card plug-in modules, such a source of supply could not directly power a typical packet-switched transmitter, whose power amplifier would require 5 watts of instantaneous power.

[0006] Therefore there remains a need for a power supply system capable of quickly delivering short bursts of high power with high efficiency, while remaining small enough for miniaturized RF communication applications.

[0007] There also remains a need for a power supply system capable of powering a low duty-cycle application requiring high instantaneous power from a battery, or other stored energy source having limited energy capacity, for substantial lengths of time.

[0008] There remains a further need for a self-contained, miniaturized, integrated power supply system capable of powering a low duty-cycle application requiring high instantaneous power from a current-limited source, such as a host computer auxiliary device power pin.

[0009] Finally, there remains a more particular need for a cost effective power supply circuit for a portable, PCMCIA-compatible radio modem, or a stand alone two-way pager system, which provides improved battery life, or alternately allows such a system to be powered directly from a host computer PCMCIA slot.

SUMMARY OF THE INVENTION

[0010] The present invention is a power supply system which provides a limited energy source (such as a low voltage battery stack or a low current computer auxiliary device power connection) to charge a high performance, low resistance capacitive device, which in turn powers a low duty-cycle, high power load circuit (such as a packet-switched radio data transmitter). The transmitter's low duty-cycle allows a low power charging source to charge the high performance capacitive device sufficiently for periodic high power pulses. The high performance capacitive device provides "load-leveling" (i.e., an averaging out of the high transient currents drawn by the time varying, high power load), effectively isolating the input charging source from the large transient currents drawn by the transmitter power amplifier during RF transmission.

[0011] A high performance capacitive device in accordance with the present invention should possess high charge storage capacity with relatively low ESR in order to meet the input power needs of the typical transmitter power amplifier. For example, capacitive devices are now available that allow relatively large amounts of electrical energy to be temporarily stored and retrieved at much higher levels than standard batteries or conventional capacitors would allow. One class of such devices are specially constructed capacitors with very high storage capabilities referred to as super-capacitors.

[0012] A super-capacitor will generally have a rating of 1.0 farad or more of storage capacity, yet will only occupy the physical volume of a standard capacitor with only 0.002 farads of capacity. These devices are typically used to provide emergency backup power in computing applications, such as for CMOS microprocessors. The component miniaturization provided by super-capacitors is important if the power supply system is to be useful for portable RE transmitter applications, such as radio modems and two-way pagers. For such units, small size is important; and in particular, it is generally desired that the components used in such devices be housed in a package that is at least functionally compatible with the physical form-factor and electrical interface requirements for host computer plug-in auxiliary modules, such as PCMCIA Type-2 or other plug-in cards. Furthermore, present manufacturing techniques have produced super-capacitors with relatively low ESR. Such super-capacitors might be used as the high performance capacitive element in the inventive system.

[0013] The load-leveling provided by the inventive power supply system allows sustained RF transmitter operation when battery cells are used as the input power source, even as the batteries weaken, and their ESR rises. The efficiencies realized can increase the useful battery life of a product by six times or more.

[0014] The inventive system also allows an input power source capable of supplying only limited current to drive a low duty-cycle application requiring high instantaneous power. For example, using this system, a PCMCIA compatible RF transmission system may be powered directly from a host computer's PCMCIA slot. In addition, the inventive system allows the use of high capacity lithium batteries as the power source despite their high ESR, resulting in even greater increases in battery life over other battery technologies.

[0015] The power supply system described herein also possesses distinct advantages over systems in which a single-use battery is used to charge a rechargeable battery stack. The inventive system provides increased battery life of the host source by avoiding continuous and inefficient charging of a battery stack. Furthermore, this system reduces the charging time from hours to seconds; allows for reductions in unit weight and size; reduces the cost and complexity of the power supply circuitry because no battery contacts or complex charging algorithms are required; simplifies the use and maintenance of the unit, since the user no longer needs to replace an additional internal battery as well as the main cells whenever one of these batteries dies; and provides more predictable operation, since the capacitive device can always be charged to the same voltage with the addition of a voltage regulator.

[0016] In addition, when a low resistance super-capacitor is used as the capacitive device, the operational life of a unit employing the inventive system is significantly longer than conventional systems, since these capacitive devices can survive over 250,000 charge cycles, while a Ni-Cd rechargeable battery can only survive about 300 to 500 charge cycles. Furthermore, a power supply system in accordance with the present invention would be less expensive, since, for example, a typical Ni-Cd stack at present would cost approximately twenty dollars, while a super-capacitor today costs only about two dollars.

[0017] Another aspect of the present invention involves balancing the voltages across individual super-capacitors when multiple super-capacitors connected in series are used as the capacitive device. Such balancing prevents an individual super-capacitor in the series from being driven to a voltage higher than its operational rating as a result of variations in leakage current between the capacitors.

[0018] As will be appreciated, the invention is capable of other and different embodiments, and its several details are capable of modifications in various respects, all without departing from the spirit of the invention. Accordingly, the drawings and detailed description are to be regarded as illustrative in nature and not restrictive. Indeed, the invention described herein is useful for any current-flow restricted power source that is required to supply high currents at a low duty-cycle. Conceivably, this system would allow a tiny button cell battery (such as those used in a wrist watch) to power a 5-watt transmitter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The present invention satisfies the needs noted above as will become apparent from the following description when read in conjunction with the accompanying drawings, wherein:

FIG. 1 is a simplified electrical schematic diagram of a direct battery power supply circuit as in the prior art.
FIG. 2 is a simplified electrical schematic diagram of a system in accordance with the present invention.
FIG. 3 is a graph comparing the hours of RF transmitter operation achieved with the prior art system of Figure 1 with those obtained with the system in accordance with the present invention of Figure 2.
FIG. 4 is a simplified electrical schematic diagram of the preferred embodiment of the present invention.
FIG. 5 is a more detailed electrical schematic diagram of the preferred embodiment of the present invention.
FIG. 6 is a simplified electrical schematic diagram of an alternative embodiment of the present invention in which a voltage regulator is connected between the high performance capacitive device and the load application circuit rather than between the limited energy source and the capacitive device.

DETAILED DESCRIPTION OF THE DRAWINGS

[0020] To appreciate some of the advantages of the inventive system, Figures 1, 2, and 3 provide a comparison between prior art technology and a simplified power supply system in accordance with the present invention.

[0021] The circuit of Figure 1 depicts the direct use of battery voltage source 1 to power high power, low duty-cycle application circuit 6, as in the prior art. Battery 1 in such a system might be a standard 9-volt Duracell® (a registered trademark of Duracell, Inc. of Bethel, Connecticut) MN1304 alkaline battery. The ESR for such a cell starts at about 0.1 ohm when the cell is new, climbs to about 2 ohms when the battery is at about 80% capacity, and eventually reaches approximately 250 ohms when the battery is nearly dead. The high ESR of the battery results in a steep voltage drop whenever load application 6 draws high current. Such a condition occurs when an RF transmitter attempts to transmit a packet, at which point the power amplifier could draw a transient current of over 1 amp.

[0022] When the load is removed from the alkaline battery at the end of a transmission, the battery cell voltage recovers somewhat from the drop experienced during transmission. At first, the cell voltage rapidly increases by about 50 millivolts, after which it continues to rise, but much more gradually. Over the course of multiple transmission cycles, however, the increasing voltage drop resulting from the battery's increasing ESR, in conjunction with the depletion of the battery during transmission, will become too great, and the alkaline cell cannot recover sufficient cell voltage within the non-transmitting portion of the cycle to power the next transmission. The battery would then be effectively dead and would have to be replaced.

[0023] Figure 2 depicts a simplified circuit in accordance with the present invention, although not the preferred embodiment. Source 2 may be any "current-limited" source, i.e., a source having a high ESR or a varying ESR, such as a lithium battery, or a source which otherwise can deliver only small currents with low instantaneous power, such as the PCMCIA slot of a host computer. High performance capacitive device 5 (denoted C) is the direct power source for high power, low duty-cycle load application 6, which might be a packet-switched RF transmitter, such as that used in a two-way paging system.

[0024] Capacitive device 5 of Figure 2 might be effectively implemented using a network of super-capacitors connected in series to provide a capacitance sufficient to drive the power amplifier of an RF transmitter for one transmit cycle at the highest expected power-draw. The interrelationships between the voltage required at capacitive device 5, the ESR of device 5, and the time duration of the load circuit transmissions may be understood by reference to the following equations:

$$V_{capmin} = V_{tmin} + V_{drop} + V_{capdis} \quad \text{— EQUATION 1;}$$

Where V_{capmin} is the minimum voltage to which capacitive device 5 must be charged for transmitter operation;

V_{tmin} is the minimum operating voltage of the transmitter power amplifier;

V_{drop} is the voltage drop caused by the current draw of the power amplifier multiplied by the capacitor's ESR [i.e., $V_{drop} = I_{draw} \times ESR$]; and

V_{capdis} is the voltage change capacitive device 5 will under go from the start of a transmit to the end.

[0025] V_{capdis} may be further defined as follows:

$$V_{capdis} = (I_{draw} \times T_{capdis})/\text{Capacitance} \quad \text{-- EQUATION 2.}$$

(I_{draw} equals the average current of the load and T_{capdis} is the length of the load pulse.)

[0026] The equations defining V_{capmin} and V_{capdis} can be combined and rearranged to provide the following capacitance relationship:

$$\text{Capacitance (C)} = (I_{draw} \times T_{capdis})/V_{capdis};$$

$$C = (I_{draw} \times T_{capdis})/[V_{capmin} - V_{trmin} - (I_{draw} \times ESR)] \quad \text{-- EQUATION 3.}$$

[0027] Considering the variations in present network protocols, the transmit time for a single packet in a packet-switched network could range from 20 milliseconds (mS) to 2 seconds depending on the nature of the network and the amount of data being sent in a given packet. Also, some conventional power amplifiers operate at voltages ranging from 3.6 volts at 2 amps to 6 volts at 800mA. Thus, a system in accordance with Figure 2, operating in a network having a single packet transmit time of 2 seconds, with the transmitter output driven by a 3.6 volt, 2 amp power amplifier, and with a charging voltage of 6.9 volts, would require a capacitance for capacitance device 5 as follows (assuming a nominal 0.3 ohm ESR for device 5):

$$C = (2.0 \text{ amps} \times 2 \text{ secs})/[6.9 \text{ volts} - 3.6 \text{ volts} - (2.0 \text{ amps} \times 0.3 \text{ ohms})];$$

$$= 1.481 \text{ farads (or approximately 1.5 farads).}$$

[0028] Thus, in this example, a device of at least 1.5 farad capacitance might be used for device 5, and if the design is to be more robust, a capacitance of about 3.0 farads or more might be desired. A capacitive module comprising multiple super-capacitors connected in series can meet such requirements.

[0029] Series connection of multiple super-capacitors is preferred in part because the working voltage for a single super-capacitor, (i.e., the voltage above which damage will occur to the super-capacitor), is typically only a few volts, resulting in insufficient stored voltage to power the average RF transmitter. While connecting super-capacitors in series overcomes the limited working voltage of a single super-capacitor, it should be appreciated that high performance capacitive device 5 could be implemented with a single super-capacitor having sufficient capacitance and working voltage ratings.

[0030] In the circuit of Figure 2, the ESR of capacitive device 5 must be kept low (generally below 2 ohms and preferably below 1 ohm) in order to provide sufficient current at sufficient voltage for transmitter operation. An approach for achieving high capacitance with low ESR is by use of a super-capacitor employing an electric double-layer structure with an activated carbon electrode. Such super-capacitors are described in Supercapacitor – Electric Double-Layer Capacitors, Vol. 2, October 25, 1996 (Japan, Tokin Corporation, Cat. No. EC-200E). Over the past year, manufacturing techniques for such super-capacitors have improved sufficiently that devices with ESR' s of less than 1 ohm are commercially available, although the minimum ESR is ultimately limited by the surface resistance between the activated carbon electrodes and the connection leads of the capacitor. Examples of such super-capacitors would include the Ultra-Capacitor manufactured by Maxwell Corporation of San Diego, CA; the Gold-Capacitor (or GoldCap) manufactured by Panasonic Corporation of Mississauga, Ontario; and the Aero-Capacitor manufactured by Polystor Corporation of Dublin, CA.

[0031] Figure 3 compares the hours of operation achieved with the circuit of Figure 1, represented by graph a, and the circuit in accordance with the present invention, Figure 2, represented by graph b. The exemplary application circuit for the Figure 3 plot is a packet-switched RF transmitter operating at a duty-cycle of about 1 percent, with power amplifier load pulses of about 1.0 second in duration. The 1 percent duty-cycle allows 100 seconds of recharge time. For this

comparison, both current-limited source 4 of Figure 2 and battery 1 of Figure 1 are assumed to be conventional 9-volt alkaline cells equivalent to Duracell® MN1304 cells. Graphs a and b plot the cell voltage of battery 1 of Figure 1 and source 4 of Figure 2 respectively at the end of each transmission. As indicated at the top of Figure 3, the transmitter power amplifier is drawing 980 mA (approximately 5 to 6 watts) during the transmit pulses.

[0032] The exemplary transmitter for the Figure 3 comparison cannot operate from an input voltage lower than 5 volts. (Of course, in practice, transmitter operation might be possible at voltages as low as approximately 3-5 volts, depending on the characteristics of the particular power amplifier.) Using the exemplary transmitter, the prior art circuit of Figure 1 only achieves approximately 7 hours of transmitter operation, as shown in the graph a, with the cessation of operation corresponding to the point where the voltage of battery 1 drops to 5 volts.

[0033] For the inventive circuit of Figure 2, however, the load-leveling provided by high performance capacitive device 5 effectively isolates current-limited source 4 from the large transient currents drawn by application circuit 6. Thus, in Figure 2, the energy of source 4 is required only for the relatively slow, and therefore less power consuming chore of charging capacitive device 5, resulting in a dramatic increase in the operational life of source 4.

[0034] The operational characteristics of the system of Figure 2 are governed by the idealized parameter relationships of Equation 1. Thus, for an exemplary transmitter system drawing 980 mA of current for 1.0 second during transmission, and assuming a 1.0 farad, 0.3 ohm ESR super-capacitor module is used for capacitive device 5, the minimum cell voltage required before transmitting (i.e., the minimum voltage to which the capacitor must be charged before transmission) is calculated from Equation 1 as follows:

$$V_{capmin} = V_{trmin} + V_{drop} + V_{capdis};$$

$$= V_{trmin} + (I_{draw} \times ESR) + (I_{draw} \times T_{capdis})/C;$$

$$= 5 \text{ volts} + (980 \text{ mA} \times 0.3 \text{ ohm}) + (980 \text{ mA} \times 1.0 \text{ sec})/1.0 \text{ farad};$$

$$= 6.27 \text{ volts (or approximately 6.3 volts)}.$$

[0035] As indicated in Figure 3, graph b, the power supply system of Figure 2 will adequately power the transmitter load circuit until the voltage of capacitive device 5 drops to 5.0 volts or less at the end of a transmission. This is the point at which the cell will not be able to supply the 6.3 volts necessary to charge the capacitor for the next transmission within the 100 second recharge time. As shown in graph b, this point is not reached until after approximately 45 hours of operation; thus, the system of Figure 2 provides an approximate six-fold increase in effective battery life and transmitter operation over the system of Figure 1.

[0036] Furthermore, in Figure 2, the high ESR of battery 1 is not present at the input of application circuit 6, and is replaced by the constant and relatively low ESR of capacitive device 5. High performance capacitive device 5 itself is not sensitive to the voltage drop associated with the ESR of source 4. It will therefore continue to charge, although at a reduced charging rate, even as the alkaline battery serving as voltage source 4 is depleted, and the battery's ESR rises to its maximum. Indeed, even if the battery were dead, the voltage of high performance capacitive device 5 would eventually rise to the normal open-circuit voltage of the cell, which for a 9-volt cell might provide sufficient power for the exemplary transmitter to send a single packet (if the cell reached the required 6.3 volts mentioned earlier).

[0037] Current-limited source 4 of Figure 2 may be a source incapable of supplying sufficient instantaneous current to power an RF transmitter directly. The low duty-cycle of application circuit 6, which in the exemplary application of Figure 3 is 1 %, allows capacitive device 5 to charge sufficiently to supply the power required by application circuit 6, even if capacitive device 5 is charged by a low current, low power source. For example, if an Ultralife® battery is used as source 4, the battery's high energy storage capacity would provide over 140 hours of operational time for the exemplary RF transmitter of Figure 3, an increase of approximately 2000% over standard alkaline cells operating without use of a high performance capacitive device such as a super-capacitor.

[0038] Where load application 6 is an RF transmitter, the duty-cycle of load 6 may be defined as follows:

$$\text{duty-cycle}\ (\%) = T_{tr} / (T_{tr} + T_{qst}) \quad \text{-- EQUATION 4;}$$

Where T_{tr} is the time duration of a transmission, and

T_{qst} is the time duration of the succeeding transmitter quiescent period (i.e., the non-transmitting interval) within an operational cycle.

[0039] In the context of the present invention, a "low" duty-cycle would typically exist where T_{qst} exceeds T_{tr} by an order of magnitude of more. With some systems it may be possible to dynamically adjust the transmitter's operating characteristics to account for differing network coverage envelope conditions and power requirements, perhaps allowing for operation at duty-cycles in the range of 50% to 75% for short intervals. Such a dynamically-controlled transmitter would still be an appropriate candidate for meeting the requirements of load application 6 so long as the average system duty cycle remains in the range of approximately 10% or less.

[0040] As a potential alternative to using a battery cell or cell stack, one might wish to power a miniaturized RF transmitter from the PCMCIA slot or other auxiliary port of a host computer. Although most host computers can supply only about 0.75 watts to the PCMCIA slot, a low energy, low current source such as this may effectively serve as source 4 in the circuit of Figure 2. Using the circuit of Figure 2, a radio modem requiring five watts of power in short pulses may be powered from a PCMCIA slot having the typical maximum current of only 150 mA.

[0041] While illustrative of the invention, the circuit of Figure 2 does not regulate the voltage across high performance capacitive device 5. Without adding some form of "step-up" regulation, the circuit of Figure 2 would not support transmitter operation from an initial input voltage that is less than that required at capacitive device 5, as per Equation 1 (i.e., a "low" voltage input could not serve as source 4 because such a source would not charge capacitive device 5 sufficiently). On the other hand, if a "high" voltage source is used as source 4, lack of voltage regulation would require use of super-capacitors having a high working voltage rating, and the use of RF transmission circuitry capable of withstanding voltages varying from 10 volts down to 5 volts, depending on the state of charge of the super-capacitors.

[0042] Figure 4 depicts the preferred embodiment of the present invention, which incorporates voltage regulator 3 connected between "limited energy" source 2 and high performance capacitive device 5. Voltage regulator 3 insures that capacitive device 5 is always charged to a relatively constant voltage within its working voltage range regardless of the voltage of source 2. Furthermore, this embodiment avoids forcing the RF transmitter power amplifier to operate at the widely varying voltages that could be present at source 2 as it discharges, given the different battery technologies that might be used.

[0043] Because of the addition of voltage regulation in Figure 4, limited energy source 2 may comprise a "voltage-limited" source, i.e., a source capable of supplying only low voltages, particularly, voltages below that required to directly charge the capacitive device in accordance with Equation 1. Source 2 of Figure 4 may also comprise a "current-limited" source, such as source 4 of Figure 2. "Voltage-limited" and "current-limited" sources are collectively designated herein as "limited energy sources."

[0044] Voltage regulator 3 may be of any construction such as would be known to those of ordinary skill in the art. Such regulators (or converters) would include the following devices: "step-up" regulators (such as a Boost converter); "step-down" regulators (such as a linear regulator or a Buck converter); "step-up/step-down" regulators (such as a Buck/Boost converter, a SEPIC converter, or a Zeta converter); and "inverting" regulators (such as a 'Cuk converter). The type of regulator employed would depend on the voltage characteristics of the circuit. For example, a step-down regulator would be appropriate if the voltage supplied by source 2 remained typically above the working voltage rating of capacitive device 5, as might be the case where source 2 is a "high" voltage source i.e., a source whose voltage is typically higher than the voltage desired for direct input to the power amplifier, such as a high voltage solar cell array or an Ultralife® lithium cell. A step-up regulator would be used where the input voltage is always less than the desired for capacitive device 5. This would include a single alkaline cell (1.5 volts) or a 3.3 volt digital supply.

[0045] Step-up/down converters are used where the input voltage may be higher or lower than the desired transmitter input voltage. This would be the case when the system is designed to operate from widely varying sources of supply. For example, a system designed to accept a 9-volt IEC-6LR61 package could encounter initial input voltages as high as 12 volts from a brand new Ultralife® cell, or as low as 5.4 volts from an almost dead Ni-Cd or alkaline cell. Thus, if the target transmitter input voltage were 6.8 volts, it would be useful to use a step-up/step-down converter.

[0046] Figure 5 depicts a more detailed implementation of the preferred embodiment. It incorporates a step-up/step-down voltage regulation scheme, allowing the system to accept both low voltage and high voltage initial inputs. In Figure 5, battery 10 is the limited energy source analogous to element 2 of Figure 4. The combination of transistors 11 and 12

provide reverse battery protection in the event that the user improperly inserts the battery into the unit. Battery **10** may be either a single cell or a multi-cell stack, including AA cells, AAA cells, a 9-volt alkaline cell stack, Ni-Cd cells, lithium cells, carbon-based cells, or any other battery technology. Alternatively, battery **10** may be removed from the system and replaced by the input power connection of a host computer auxiliary device part (such as a PCMCIA slot), a solar cell array, or a single solar cell.

[0047] For the embodiment of Figure 5, voltage regulation is preferably provided by the combination of an LT1307 step-up switching regulator **15** (from Linear Technology Corp. of Milpitas, CA), Schottky diode **16**, and a linear regulator made up of a comparator circuit (built into the LT1307) and FET **17**. These elements form a step-up/step-down converter which implements voltage regulator **3** of Figure 4. In this configuration, if the voltage of battery **10** is between 5 volts and 6.8 volts, such as in the case of a discharged Ni-Cd cell stack, switching regulator **15** boosts it to approximately 6.8 volts. If the input from battery **10** is from 6.8 to 12.5 volts, such as with a fresh Ni-Cd or lithium cell, the linear regulator component provides over-voltage protection, holding the output level at approximately 6.8 volts. The "step-down" component of the regulator could be implemented using a SEPIC or a ZETA converter instead of the linear regulator of this embodiment.

[0048] In Figure 5, the output of the voltage regulation circuit formed by elements **15**, **16**, and **17** is connected directly to the super-capacitor network formed by super-capacitors **20**, **21**, and **22**. The working voltage rating of one of these super-capacitors is only about 2.3 to 2.4 volts; but, connected in series, these super-capacitors are driven to produce a substantially constant voltage having a value within the range of approximately 6.7 volts to approximately 7.0 volts when the super-capacitors are fully charged. During the transmit/quiescent cycle, the voltage across the super-capacitors eventually drops to the minimum operating voltage of circuit **40**, which could be approximately 5 volts, approximately 3.5 volts, etc., depending on the operating characteristics of transmitter power amplifier **41**. In the exemplary embodiment, the power supply system would accept an initial input voltage from source **10** of 5 to 12 volts and nevertheless produce an voltage output which remains within the range of 6.8 volts to 5 volts. The components of RF application circuit **40**, therefore, need only accommodate input voltages within this voltage range.

[0049] While series connection of super-capacitors **20**, **21**, and **22** overcomes the general working voltage limitation, leakage current and component variations between the capacitors can lead to a voltage imbalance across the individual capacitors. Such a voltage imbalance can result in one or more of the capacitors in the stack operating at a voltage that exceeds the working voltage of that capacitor. Placing resistors in parallel with the super-capacitors would avoid this problem; however, if resistors alone were used, the circuit would have a high standby current which would ultimately decrease the life of battery **10**.

[0050] In Figure 5, a technique known as "active cell balancing" is employed, allowing the circuit to operate with nearly zero standby current. The active cell balancing circuit consists of resistors **52** through **54**, which form a resistor divider circuit, low power operational amplifiers **60** and **61**, which are configured as voltage followers, and resistors **50** and **51**, which limit current flow from the operational amplifiers to the minimum values required to maintain voltage balance among the cells. In Figure 5, the resistor divider determines the required cell voltages, and the voltage followers force the capacitors to track the resistor voltages regardless of the leakage current. This circuitry ensures that each capacitor takes an equal voltage share. Use of the voltage followers allows resistors **52** to **54** to be three orders of magnitude greater in resistance than they would be in an all resistive cell balancing scheme without operational amplifiers **60** and **61**. Thus, this configuration would reduce the leakage current by three orders of magnitude over resistor-only cell balancing. The combination of super-capacitors **20**, **21** and **22**, resistors **50**, **51**, **52**, **53** and **54**, and operational amplifiers **60** and **61** comprise a network which corresponds to high performance capacitive device **5** of Figure 4.

[0051] In Figure 5, power amplifier **41** for RF transmitter **40** is a very high-current load, drawing approximately 1000 mA or more during transmissions. It is connected directly to the super-capacitor network. In this embodiment, power amplifier **41** should be selected to operate over the 6.8 to 5 volt voltage range previously mentioned, since at the beginning of a long transmission the voltage supplied to it by the super-capacitor network will be about 6.8 volts, but will gradually decrease as the super-capacitors discharge.

[0052] An alternative embodiment of the circuit of Figure 4 is depicted in Figure 6. The difference between these embodiments is that in Figure 6, the voltage regulator **3** is connected between capacitive device **5** and application circuit **6**. In this circuit, source **2** would typically be a voltage-limited (or low voltage) source. This allows a single super-capacitor having a very high capacitance rating to be used as device **5** instead of several super-capacitors in series connection. In this embodiment, load-leveling is achieved by storing the same amount of energy as in the other embodiments disclosed, but the storage is done at a lower voltage. Load application circuit **6** (e.g. an RF transmitter) is then run directly from regulator **3**, which in this case would be a step-up switching regulator operating from the output of the super-capacitors. With this embodiment, however, switching regulator **3** is required to handle very high currents, and consequently its components will be quite large physically. For example, it would be expected that a 1.2 volt source such as a Ni-Cd AA battery powering a 1000 mA, 6.8 volt load would require the voltage regulator to operate at over 7 amps on its input. While such an embodiment would function, it would not be optimal for applications in which component miniaturization and reduced power dissipation concerns are paramount.

[0053] Having described in detail the preferred embodiment of the present invention, including its preferred modes of operation, it is to be understood that this operation could be carried out with different elements and steps. This preferred embodiment is presented only by way of example and is not meant to limit the scope of the present invention which is defined by the following claims.

Claims

1. A power management system comprising:

   a low duty-cycle, high power load circuit;
   at least one capacitive device, electrically connected to the load circuit, that provides primary electrical power to the load circuit; and
   a limited energy source, electrically connected to the capacitive device, that provides a source of electrical charge for the capacitive device.

2. The system of claim 1, wherein the capacitive device comprises at least one super-capacitor.

3. The system of claim 2, wherein the capacitive device comprises plural super-capacitors connected in series.

4. The system of claim 3, further comprising a voltage balancing circuit that maintains an equalized voltage across each super-capacitor.

5. The system of claim 4, wherein the voltage balancing circuit comprises:

   plural operational amplifiers connected as voltage followers and electrically connected with a resistor divider network, wherein the voltage followers and the resistor divider network are electrically connected to the super-capacitors so that the voltage across each super-capacitor is forced to the value of the resultant voltage of the resistor divider network.

6. The system of claim 1, wherein the limited energy source is at least one battery cell.

7. The system of claim 1, wherein the limited energy source is a power connection for a host computer auxiliary device port.

8. The system of claim 1, wherein the limited energy source is a photo-voltaic device.

9. The system of claim 8, wherein the photo-voltaic device is a solar cell array comprising at least one solar cell.

10. The system of claim 1, wherein the duty-cycle of the load circuit does not exceed an average value of 10 percent.

11. The system of claim 10, wherein the duty-cycle of the load circuit may be a value in the range between and including 10% and 75% for limited intervals.

12. The system of claim 1, wherein the load circuit requires input power greater than 1 watt during operation.

13. The system of claim 1, wherein the load circuit requires input power greater than l watt for 20 mS to 2 seconds during operation.

14. The system of claim 6, wherein the load circuit, the capacitive device, and the battery are enclosed in a single housing that is physically and electrically compatible with a host personal computer auxiliary device port.

15. The system of claim 14, wherein the housing is PCMCIA compatible.

16. The system of claim 1, wherein the load circuit is a packet-switched radio- frequency transmitter.

17. The system of claim 1 further comprising:

   a voltage regulation device electrically connected to the capacitive device for regulating the voltage input to the

capacitive device to produce a substantially constant voltage across the capacitive device at the point of full charge.

18. The system of claim 17, wherein the substantially constant voltage has a value within the range of approximately 6.7 volts to approximately 7.0 volts.

19. The system of claim 17, wherein the voltage regulation device comprises a switching regulator.

20. The system of claim 19, wherein the switching regulator is a step-up converter.

21. The system of claim 19, wherein the switching regulator is a step-up/ step-down converter.

22. The system of claim 19, wherein the switching regulator is a step-down converter.

23. The system of claim 17 wherein the voltage regulation device comprises a linear regulator.

24. The system of claim 17, wherein the voltage regulation device comprises a switching regulator in combination with a linear regulator.

25. A circuit for supplying electrical power to a packet-switched, RF transmitter comprising:

a super-capacitor network including a plurality of super-capacitors, electrically connected to the transmitter, that provides primary electrical power for the transmitter; and
a limited energy source, electrically connected to the super-capacitor network, that provides a source of electrical charge for the super-capacitor network.

26. The circuit of claim 25, wherein the limited energy source is at least one battery cell.

27. The circuit of claim 25, wherein the limited energy source is a power connection for a host computer auxiliary device port.

28. The circuit of claim 25, wherein the super-capacitors are connected in series.

29. The circuit of claim 28, wherein the transmitter, the super-capacitor network, and the battery cells are enclosed in a single housing that is physically and electrically compatible with a host personal computer auxiliary device port.

30. The circuit of claim 29, wherein said housing is PCMCIA compatible.

31. The circuit of claim 25 further comprising:

a voltage regulation device electrically connected to the super-capacitor network that regulates the voltage across the super-capacitor network.

32. The circuit of claim 31, wherein the voltage regulation device comprises a switching regulator in combination with a linear regulator.

33. An RF data transmission system comprising:

an RF transmitter that transmits digitally modulated data, the transmitter having an active transmission time interval T_1 and a quiescent time interval T_2, where T_2 is substantially larger than T_1;
at least one super-capacitor, electrically connected to the transmitter, that supplies input power to the transmitter; and
a limited energy source, electrically connected to the super-capacitor, that charges the super-capacitor.

34. The transmission system of claim 33, wherein T_2 is greater than T_1 by at least one order of magnitude.

35. A miniaturized packed-switched RF transmission system comprising:

an RF transmitter, having output circuitry and a power amplifier that drives the output circuitry, for producing RF transmissions at a low duty-cycle;
a high capacity, low resistance capacitive device electrically connected to the power amplifier for supplying power to the power amplifier during transmission; and
a limited energy source electrically connected to the capacitive device for charging the capacitive device.

36. A method of supplying power to a high power load application circuit comprising the steps of:

operating the load application circuit at a low duty-cycle;
supplying input power to the load application circuit from a high capacity capacitive device; and
charging the capacitive device from the voltage supplied by a limited energy source.

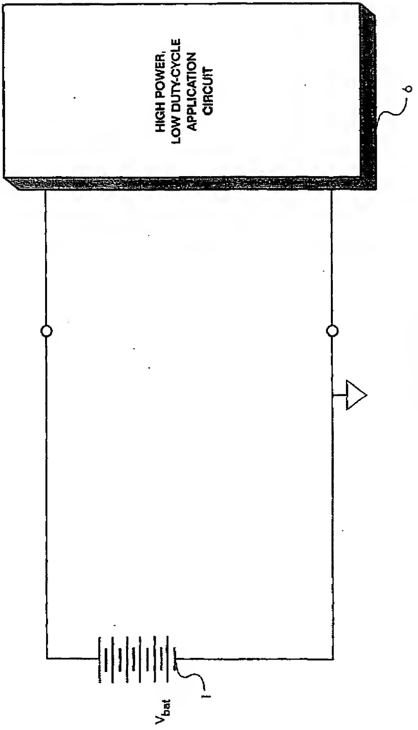
37. The method of claim 36 further comprising the step of regulating the voltage supplied by the limited energy source such that the capacitive device is charged to a substantially constant voltage level at the point of full charge.

38. A system for supplying electrical power comprising:

a low duty-cycle, high power load circuit;
capacitive means for providing primary input electrical power to the load circuit at high current; and
a means for providing electrical charge to the capacitive means.

39. A power supply circuit for use with an RF transmitter that transmits periodic high-power pulses of information, comprising:

at least one super-capacitor for supplying high current pulses of energy to the transmitter; and
means for charging the super-capacitor.



PRIOR ART

Figure 1

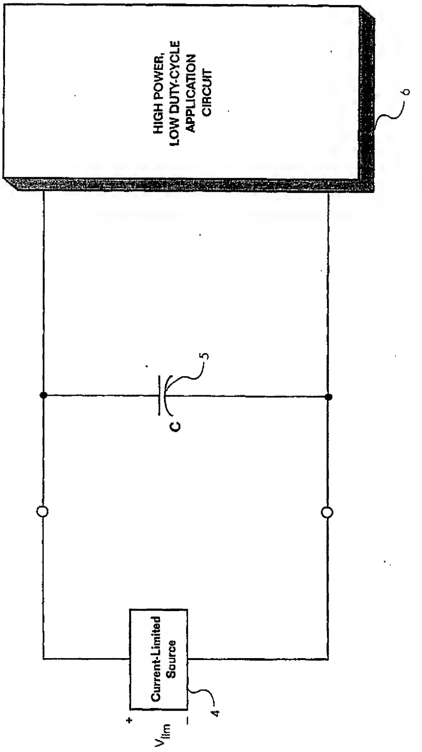

HIGH POWER,
LOW DUTY-CYCLE
APPLICATION
CIRCUIT
6
5
C
Current-Limited
Source
4
+
V_{lim}
–

Figure 2

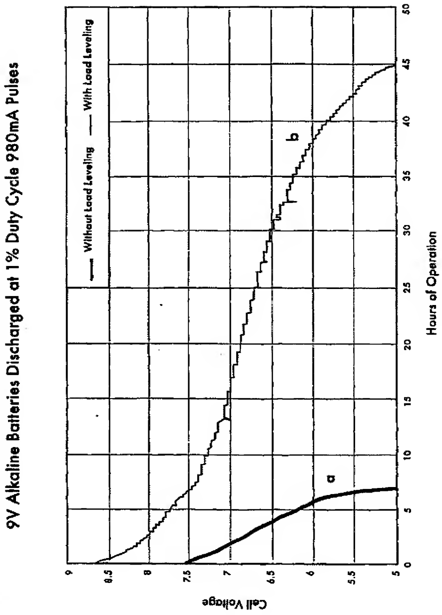

9V Alkaline Batteries Discharged at 1% Duty Cycle 980mA Pulses
Without Load Leveling
With Load Leveling
a
b
Cell Voltage
9
8.5
8
7.5
7
6.5
6
5.5
5
Hours of Operation
0
5
10
15
20
25
30
35
40
45
50

Figure 3

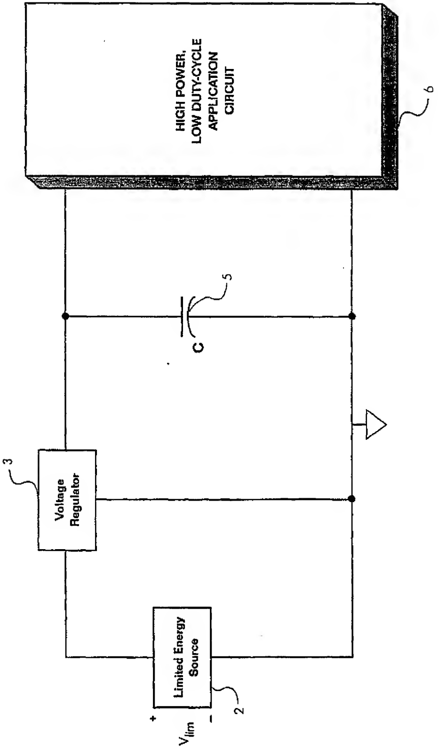
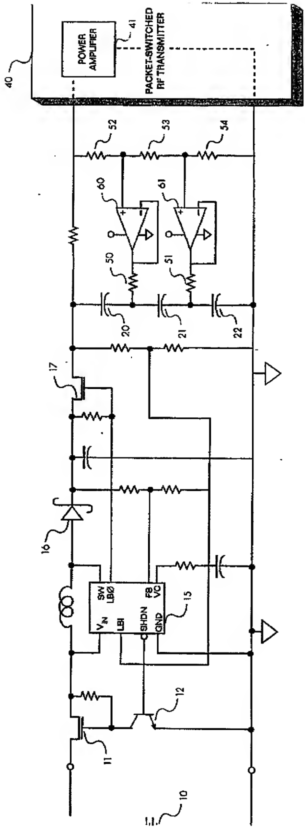

HIGH POWER,
LOW DUTY-CYCLE
APPLICATION
CIRCUIT
6
5
C
3
Voltage
Regulator
Limited Energy
Source
2
+
V_{lim}
–

Figure 4


POWER AMPLIFIER
PACKET-SWITCHED RF TRANSMITTER
SW
LBØ
FB
VC
VIN
LBI
SHDN
GND
10
11
12
15
16
17
20
21
22
40
41
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51
52
53
54
60
61

Figure 5

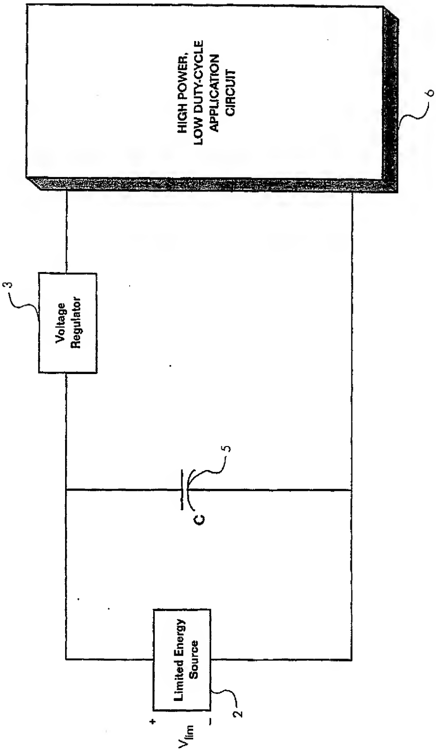
HIGH POWER,
LOW DUTY-CYCLE
APPLICATION
CIRCUIT
6
3
Voltage
Regulator
5
C
Limited Energy
Source
2
+
V_{lim}
–

Figure 6

(19) Europäisches Patentamt
European Patent Office
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(54) **Improved power supply system for a packet-switched radio transmitter**

(57) An improved power supply system involves load-leveling the large transient currents drawn by a high power, low duty-cycle load application circuit by means of a high performance capacitive charge storage device, such as a super-capacitor or a network of super-capacitors. The improved power supply system allows the high power load application circuit to be driven by a limited energy power source, such as a battery or the power supplied to a PCMCIA slot by a host computer. When the input voltage source is a battery, the improved power supply system allows for a substantial increase in the battery's operational life. The inventive system is particularly useful for managing power supply requirements for miniaturized wireless transmission systems, such as two-way pagers or radio modems, which employ low duty-cycle packet-switched RF transmitters.

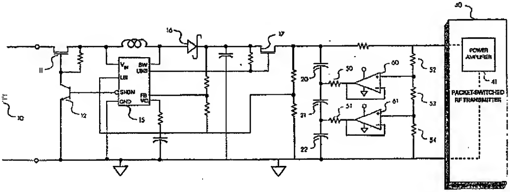

Figure 5

EP 0 902 547 A3

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EUROPEAN SEARCH REPORT

Application Number
EP 98 11 7379

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A	* column 5, line 15 - column 6, line 30; figures 2-4 *	4,5,7-9, 14,15, 17-24, 27, 29-32,37	
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A	* column 14, line 33 - line 60; figure 4B *	5	
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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	27 April 2001	Andersen, J.G.

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